

NASA PLUM BROOK's B-2 TEST FACILITY – THERMAL VACUUM AND PROPELLANT TEST FACILITY

M.T. Kudlac¹, H.F. Weaver² and M.D. Cmar³

¹NASA Glenn Research Center, Lewis Field
2100 Brookpark Road
Cleveland, Ohio, 44135, USA

²NASA Glenn Research Center, Plum Brook Station
6100 Columbus Avenue
Sandusky, Ohio, 44870, USA

³Sierra Lobo Inc, NASA Glenn Research Center, Plum Brook Station
6100 Columbus Avenue
Sandusky, Ohio, 44870, USA

ABSTRACT

The National Aeronautics and Space Administration (NASA) Glenn Research Center (GRC) Plum Brook Station (PBS) Spacecraft Propulsion Research Facility, commonly referred to as B-2, is NASA's third largest thermal vacuum facility. It is the largest designed to store and transfer large quantities of liquid hydrogen and liquid oxygen, and is perfectly suited to support developmental testing of upper stage chemical propulsion systems as well as fully integrated stages. The facility is also capable of providing thermal-vacuum simulation services to support testing of large lightweight structures, Cryogenic Fluid Management (CFM) systems, electric propulsion test programs, and other In-Space propulsion programs.

A recently completed integrated system test demonstrated the refurbished thermal vacuum capabilities of the facility. The test used the modernized data acquisition and control system to monitor the facility. The heat sink provided a uniform temperature environment of approximately 77K. The modernized infrared lamp array produced a nominal heat flux of 1.4 kW/m². With the lamp array and heat sink operating simultaneously, the thermal systems produced a heat flux pattern simulating radiation to space on one surface and solar exposure on the other surface.

KEYWORDS: Test Facility, Altitude, Thermal Vacuum, Propulsion, Cryogenic, Propellant, Cold Wall, Heat lamps

INTRODUCTION

The B-2 test facility was designed in the 1960's to provide a test bed for upper stage vehicles. It is a high altitude facility capable of testing full scale launch vehicles in a simulated space environment. The facility can provide long term space simulation combined with multiple engine firings representing the full mission profile of an upper stage vehicle. Over the last 5 decades the core capabilities of the facility have been used to test a wide variety of hardware in addition to upper stages. The facility is systematically undergoing refurbishment and modernization to continue to meet customer needs.

FACILITY CORE CAPABILITIES

The B-2 test facility is located at Plum Brook Station, in Sandusky, Ohio. Plum Brook Station is the 2590 hectare (6400 acre) field station of NASA Glenn Research Center. The test facilities at Plum Brook are separated by large distances to safely support testing of large quantities of gaseous or cryogenic propellants necessary for rocket engine and component testing. An artist's rendering of the B-2 Facility is shown in FIGURE 1.

The center of the B-2 facility is a large vertical vacuum chamber. The chamber consists of a cylindrical section that is 14 m (46 ft) high by 11.5 m (38 ft) topped with a hemispherical head of the same diameter. The lower end of the chamber has a 3.4 m (11 ft) diameter by 11.3 m (37 ft) long exhaust duct sealed with a high vacuum valve. Typical test article installation into the test chamber is via a hinged hatch at the top of the hemispherical dome using an 18,100 kg (20 ton) overhead crane. The hatch is 8.2 m (26.75 ft) in diameter. The nominal test article envelope is 6.7 m (22 ft) diameter by 15.8 m (52 ft) maximum vertical clearance. Personnel and small equipment access is available via 1.8 meter (6 ft) diameter circular doors located at the bottom of the chamber and at 12.5 meters (41 ft) above the bottom of the chamber. Numerous high-vacuum penetrations exist at multiple elevations for routing of fluids and electrical power, or signals internal to the chamber without compromising the vacuum environment. Vacuum levels in the 10^{-5} Pa (10^{-7} torr) are achieved using oil diffusion pumps backed by a series of mechanical pumps. Cold caps on the diffusion pumps are used to minimize oil back-streaming.

Located below the vacuum chamber is a large concrete structure known as a "spray chamber". The spray chamber handles the test article exhaust for engine thrust levels of 444,822 N (100,000 lbs). The spray chamber is 20 m (67 ft) diameter by 36 m (119 ft) high. The spray chamber can be evacuated to approximately 1 kPa (0.15 psia) independent of the vacuum chamber using steam ejectors. The spray chamber is filled with 6.6 million liters (1.75 million gallons) of cooling water. During an engine firing at altitude conditions, the cooling water is circulated to a series of spray bars which produce a fine water spray to quench and condense the exhaust. Non-condensable components are exhausted via the steam ejectors. Cooling is also provided on the back side of the diffuser duct and to the steam ejectors. Fuel and oxidizer abort (dump) tanks are also located in the spray chamber and can be used to safe the facility in the event of a test article anomaly.

LN2 Tank

Test Article
Insertion
Hatch

Personnel
Doors

Exhaust
Diffuser

Spray
Bars

Propellant
Abort
Tanks

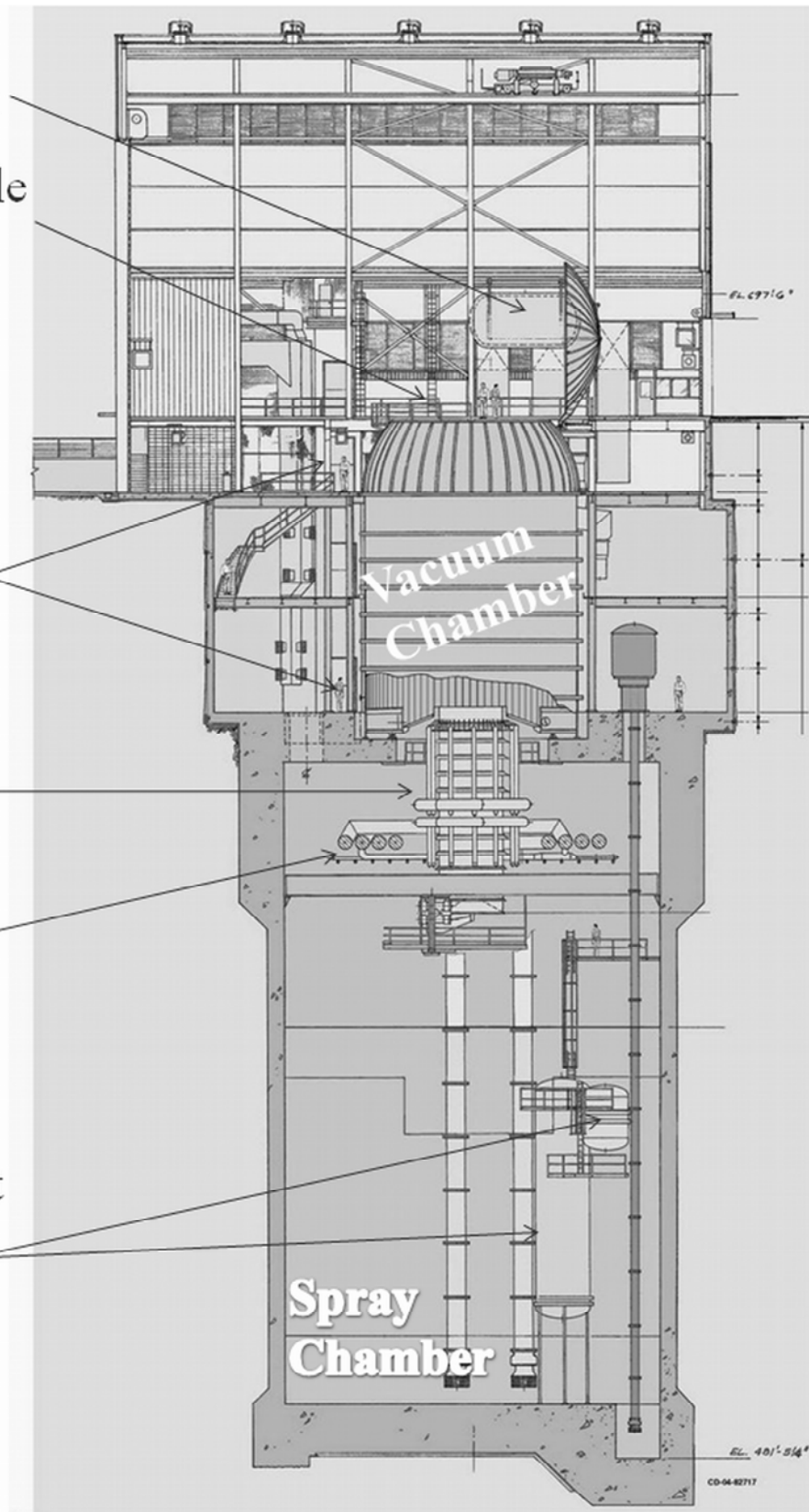


FIGURE 1. An artist's rendering of the B-2 test chamber. The vacuum chamber is shown with the top hatch open. The LN₂ vessel that feeds the heat sink is visible near the open top cap. The water cooled diffuser duct and spray chamber are shown below the vacuum chamber. The visible propellant abort tanks in the spray chamber protect facility/test hardware in the event of a test article anomaly.

Thermal simulation for the test article is achieved using a liquid nitrogen heat sink and an infrared lamp array. The interior surface of the stainless steel vacuum chamber is lined with a liquid nitrogen (LN₂) heat sink or cold wall. The heat sink covers the entire interior of the test chamber reducing the internal clearance to 10.4 m (34 ft) diameter and 17 m (56 ft) high. The access hatch or top cap has a separate liquid nitrogen heat sink. The only portion of the chamber not having integrated heat sink coverage is a 6.7 m (22 ft) diameter circle on the floor level of the chamber. The heat sink consists of a series of finned tubes connected to an upper and lower manifold. The fins are arranged parallel to the chamber wall resulting in an optically dense surface. The heat sink is flooded with LN₂ providing a background temperature of 77 K (140°R). The heat sink is constructed of copper to optimize conduction. An infrared lamp array installed in the vacuum chamber provides a heat flux pattern equivalent to a nominal solar constant, 1.367 kW/m². The array is configurable and can be independently controlled by twelve (12) zone controllers. When fully configured, each zone contains forty-eight (48) 0.75 kW lamps resulting in a total array power of 432 kW. Each zone controller is rated at 50 kW yielding a system capacity of 600 kW. When the heat sink and infrared lamp array are used simultaneously, a test article can be exposed to a thermal pattern representing deep space on one surface and the solar expose on a separate surface.

The test building is designed for propellant testing. Components in the building have been selected to be non-incendiary or are located in purged/pressurized enclosures. During propellant testing, personnel are evacuated from the test building. Tests are conducted from a remote control room located 777 m (2,550 ft) west of the test building.

Propellants are stored in bulk outside of the test building. On-site liquid hydrogen (LH₂) storage capacity is 128,704 L (34,000 gallon). B-2's storable fuel (fuel which is liquid at ambient temperatures) storage capacity is 24,605 L (6500 gal). The liquid oxygen (LO₂) storage capacity is 45,425 L (12,000 gallon). Gaseous nitrogen (GN₂) and gaseous helium (GHe) are used to provide purge and pressurization.

DECADES OF TESTING

The B-2 test facility was designed to test upper stage vehicles and engines at simulated altitude conditions. The size and capabilities of the thermal vacuum chamber in addition to the ability to simultaneously test fuels and oxidizers has pushed B-2 outside of its original mission of testing upper stage vehicles.

During the development of the Centaur vehicle approximately seventy-three (73) tests were performed at B-2 [1]. Some of the Centaur development tests involved tanking and chilldown leading up to ignition and restart testing and finally full duration mission simulation tests. Upper stage test capabilities were also used during the Delta III [2] programs in the 1990's. The B-2 vacuum chamber was also used to develop engine chill down techniques for both the Atlas Reliability Enhancement Program (AREP) [3] and Delta III Programs [2]. Altering the chill down for the engines led to lower over board propellant losses leading to enhanced payload capability.

B-2 has also been involved in development of small thrusters, payloads, and components for use in upper atmosphere and space environments. In small thruster test programs the facility exhaust systems are not used. After the vacuum chamber has reached altitude conditions, the thruster is fired for short durations. Due to the size of the vacuum chamber, pressures do not increase significantly. Thruster programs have included Pulse Detonation Rocket Engine (PDRE). Arcjet plume interaction with solar

arrays was also studied in the vacuum chamber [4]. Ground testing of payloads in the B-2 chamber has provided valuable information. The information gained by testing in a thermal vacuum chamber has contributed to mission successes. Sounding rocket experimental payloads that were pre-flight tested at B-2 to confirm operation under vacuum and to calibrate systems include Space Powered Experiments Aboard Rockets (SPEAR) [5] and Excitation by Electron Deposition (EXCEDE). For similar reasons, balloon payloads including Transition Radiation Array for Cosmic Energetic Radiation (TRACER) [6] and Cosmic Ray Electron Synchrotron Telescope (CREST) have also done pre-flight thermal vacuum testing. The test chamber and cold wall were used for airbag inflation tests for the Mars Pathfinder [7] and Mars Exploration Rover (MER) [8]. FIGURE 2 shows a Centaur Stage and the TRACER test package positioned over the B-2 vacuum chamber.

The B-2 chamber has also been used for non-aerospace applications such as drying personnel records in the 1970's by cyclically heating and evacuating the chamber. Heating was accomplished by introducing steam rather than LN₂ into the heat sink.

B-2 is continuously meeting with customers to discuss testing options that include tanking tests, simultaneous fuel/oxidizer cryogenic fluid management (CFM) tests, and engine tests.

FACILITY MODERNIZATION AND REFURBISHMENTS

In 2006, an effort to systematically refurbish all major facility subsystems and ancillary infrastructure equipment was started [9]. The aim of the refurbishment was to modernize the facility in phases starting with the vacuum system and proceeding to the thermal simulation system and then the cryogenic propellant and exhaust systems. The facility data acquisition and controls systems have also undergone extensive modernization.

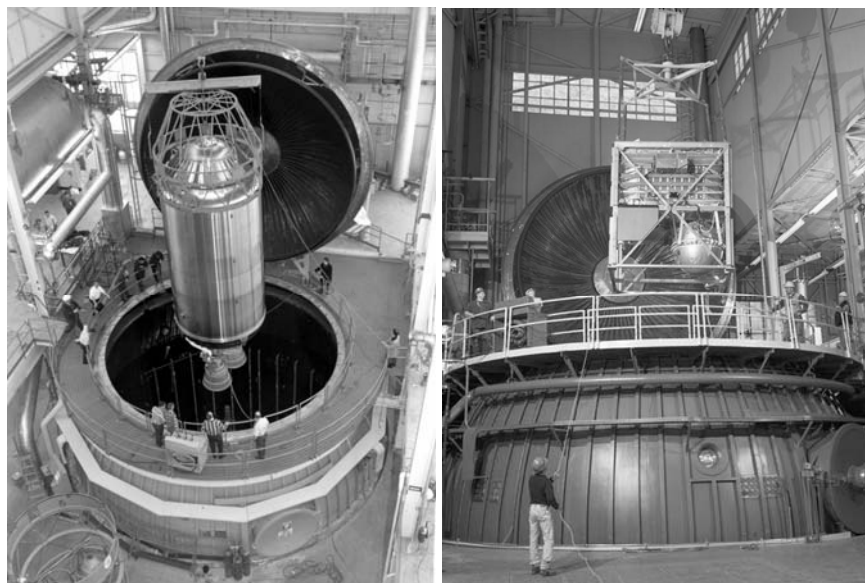


FIGURE 2. Centaur Stage (left) and TRACER test package (right) positioned over B-2 Vacuum Chamber

The vacuum system and test chamber were completely refurbished. All vacuum pumps were completely rebuilt. In addition to replacing the existing instrumentation, additional health monitoring and diagnostic instruments were installed. The chamber was extensively leak checked and non-destructive evaluation was performed to verify the structural integrity of the vacuum chamber and system. The thermal simulation system was also refurbished. Non-destructive evaluation of the heat sink and the LN₂ supply and vent lines was performed. The controllers for the infrared lamp array were replaced with state of the art systems. Following the completion of refurbishment of the thermal simulation system, an integrated systems test was conducted to demonstrate performance.

The facility control system was completely replaced in 2006 with a state of the art programmable logic control (PLC) based system. Graphical user interfaces (GUI) are used for operations. The control system is used to monitor facility systems and keeps a log of key parameters. The control system was designed to be easily reconfigured to support specific test package requirements. Cabling between the control room and test facility has been replaced with a fiber optic network. Remote video monitoring of the test facility was also upgraded. The data acquisition system is separate from the control systems. Data is time synchronized with the control system using an IRIG-B protocol. The test data is digitized in a data room at the test facility and is immediately transmitted to data recording units located in the control room. The fiber optic network has been designed to minimize time delays between data acquisition at the test site and transmission to the control room. Currently there are 488 channels of low speed, 32 channels of high speed, and 64 channels of discrete input in the data system. The data system can acquire data up to 4,000 samples per second in the low speed and up to 256,000 samples per second in high speed. Slower sampling rates are also achievable and are set typically at 125 samples per second. After the data has been recorded, it is post processed for customer review. FIGURE 3 shows the modern control room for B-2.

Refurbishment of the LH₂ and GHe system are on-going. Plans have been developed for the renewal of the LO₂ and exhaust systems.



FIGURE 3. Modernized Control Room for B-2. Graphical user interfaces (GUI) for the programmable logic control (PLC) based system are visible in the foreground. Along the back wall, video monitors display test site camera images. The independent data system consoles are not shown in this view.

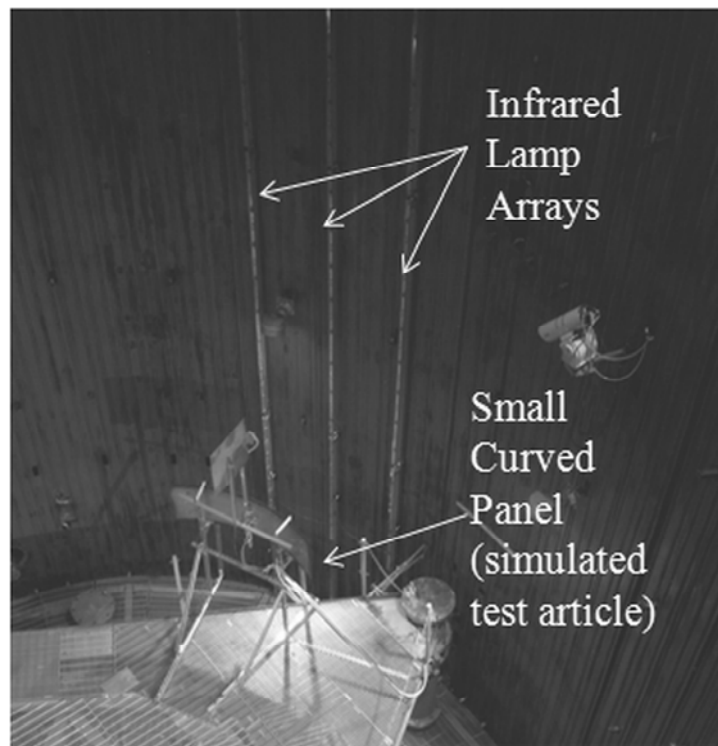


FIGURE 4. In the foreground of the picture is a test article designed to represent the rounded wall of a tank. Visible in the background are 3 infrared lamp arrays.

Thermal Vacuum Integrated System Test

For the thermal vacuum integrated system test, a simulated test article was located approximately 3.7 m (12 ft) above the vacuum chamber floor. Three (3) zones of infrared lamps were installed. A vacuum level of 9×10^{-4} Pa was achieved rather than the rated 10^{-5} Pa due to a leak in a camera purge. During the test, heat flux equivalent to one solar constant was measured at the test article. The lamp arrays were operated using both open and closed loop control. Fine tuning of the heat flux was demonstrated by controlling the power input to the lamp arrays. The arrays were operated both with and without the heat sink (body and top cap) filled with LN₂. When the heat sink is at 77 K, slightly more power is required to achieve the same heat flux at the test article. Steady state temperature readings were achieved approximately 5 hours after filling the heat sink. (It should be noted that the simulated test article reached steady state temperature quickly due to the lack of insulation.) See FIGURE 4 for a picture of the simulated test article installed in the vacuum chamber.

CONCLUSIONS

The B-2 facility was originally designed as a thermal vacuum facility to test upper stages over the entire operational life including engine operation at altitude conditions. Over the years, the facility has been used for other tests requiring vacuum, thermal vacuum, or altitude-engine operations. Strategic investments have been made to modernize and refurbish facility systems and infrastructure. A recently completed thermal vacuum integrated systems test demonstrated the successful operation of the

newly refurbished systems. Plans for continued investment in the propellant and exhaust systems will result in a fully revitalized facility.

REFERENCES

1. Grosbeck, W., Baud, K., Lacovic, R., Tabata, W., and S. Szabo, "Propulsion System Tests on A Full Scale Centaur Vehicle to Investigate 3-Burn Mission Capability of the D-1T Configuration," NASA TM X-71511.
2. Meyer, M., Dickens, K., Skaff A., Cmar M., VanMeter M., and M. Habersbusch, "Performance of Spacecraft Propulsion Research Facility During Altitude Firing Tests of the Delta III Upper Stage," NASA TM 1998-208477.
3. Schuster J., Howell D, Lucas S., Habersbusch M., Gaby J., Van Dresar N., and M. Wadel, "Cold Flow Testing of Revised Engine Chillover Methods for the Atlas Centaur," *AIAA 96-3014*.
4. Galofaro, J., Vayner, B., Hillard, G., and M. Chornak, "Thruster Plume Plasma Diagnostics: A Ground Chamber Experiment for a 2-Kilowatt Arcjet," NASA TM 2005-213837.
5. Rochefort, J., O'Connor, L., Sukys, R., Poirier, N., and R. Morin, "Instrumentation, Control, and Communication Systems for Sounding Rockets and Shuttle-Borne Experiments," PL TR 91-2175.
6. Dietrich Muller, "Status", TRACER home page, <http://tracer.uchicago.edu/status.html>, date accessed May 13, 2011.
7. Cadogan, D., Sandy, C., and M. Grahne, *Acta Astronautica* **50**, pp. 633-640 (2002)
8. Stein, J. and C. Sandy, "Recent Developments in Inflatable Airbag Attenuation Systems for Mars Exploration," *AAF-061*.
9. Hill, G., Weaver, H., Kudlac, M., Evans, R., and C. Maloney, "Space Propulsion Research Facility (B-2) An Innovative, Multi-Purpose Test Facility," Aerospace Testing Seminar 2011.